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Retrofitting pipelines with cured-in-place linings for earthquake-induced ground deformations

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ABSTRACT

Cured-in-place linings (CIPLs) are flexible polymeric linings that can be used for the seismic retrofit of underground pipelines in situ. This paper focuses on the earthquake performance of 150-mm diameter pipelines with defects, such as weak joints and circumferential cracks, which are reinforced with CIPLs. The most critical mode of deformation is in the axial direction of the pipeline reinforced with linings. Full-scale tension tests show that CIPL de-bonding before rupture closely depends on the internal pipe pressure. The results of a finite element model accounting for CIPL de-bonding as a Mode II fracture propagation compare favorably with full-scale test results for different internal pressures. Quasi-static and dynamic tests on CIPL-reinforced pipes show that the CIPL can fail as the lining protrudes from a circumferential crack that opens and closes under transient ground motion, thus "pinching" off the lining. Simplified analytical and finite element models are used to calculate the peak ground velocity and periods leading to "pinching" failure. Recommendations are made for applying the findings of this study for the in situ strengthening of the underground pipelines.

1. Introduction

Cured-in-place linings and pipes (CIPLs and CIPPs, respectively) are used to rehabilitate underground pipelines in situ, thereby increasing the service life of underground infrastructure through trenchless construction procedures [29]. CIPLs and CIPPs are flexible and rigid structural tubes, respectively, of woven fabric or fiberglass reinforced felt saturated with epoxy or thermosetting resin, inserted and cured in existing pipelines. The linings secure continuity of pipeline flow, prevent leakage and intrusion, and provide variable degrees of structural reinforcement [5,11]. The main goal of this paper is to explore the performance of pipelines reinforced with CIPLs to earthquake-induced ground deformations and thereby address an important deficiency in current practice, namely the lack of verification of trenchless pipe lining technology for retrofit of existing lifelines against earthquake effects.

CIPLs and CIPPs have benefitted from comprehensive research [2,3,9,13,16,17,23,25,27], and show promise with respect to in situ retrofitting of underground utilities against earthquake-induced transient and permanent ground deformation [14,15,54–58]. Experimental and analytical work by Netravali et al. [30,31] and Jeon et al. [28] demonstrate the effectiveness of CIPLs for in situ strengthening of cast iron (CI) pipelines that have full circumferential cracks and weak joints against the effects of excavation-induced ground deformation. Jeon et al. [28] report on large-scale laboratory tests during which a CIPL-reinforced CI pipeline with a circumferential crack was able to accommodate the excavation-induced soil movements and then sustain an additional one million cycles of traffic-induced deformation without leakage. Zhong et al. [58] report on experiments performed with twin shake tables to induce quasi-static and seismic ground motions in pipelines reinforced with CIPLs. The results show that the retrofitted pipelines were able to accommodate high intensity transient ground motions, consistent with some of the highest near-field ground velocities ever measured. The CIPLs therefore provide substantial benefits for seismic strengthening in addition to the rehabilitation of aging underground infrastructure.

This paper begins with a description of the CIPL and ductile iron (DI) pipeline used in the experimental and numerical work. It reviews the pipeline deformation modes caused by permanent and transient ground deformations (PGD and TGD, respectively). Full-scale static and dynamic tests results are presented to evaluate the performance of

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CIPL-reinforced pipelines with weak joints or circumferential cracks under PGD and TGD. A one-dimensional finite element model accounting for the CIPL de-bonding under axial tension is presented and compared with the static tests results under different internal pressures. A simplified analytical model for the calculation of the weak joint or crack opening when pipeline is subjected to seismic ground waves is also presented. Recommendations are made for applying modeling and experimental results for the seismic retrofit of underground pipelines.

2. Cured-in-place linings

AWWA [5] classifies the pipe linings into structural, semi-structural and non-structural and four different classes (Class 1–4). Semi-structural linings are designed to cover small holes or gaps in the host pipe and are normally classified as Class 2 or 3. Both Class 2 and 3 linings provide internal corrosion protection and can withstand the maximum allowable operating pressure (MAOP) of the pipeline. Class 3 linings have also inherent ring stiffness, meaning that the can provide shear stiffness at the location of defects, compared to Class 2 linings. The CIPL lining used in this study is classified as a Class 2 and is commercially available as Starline2000®, which is installed by Progressive Pipeline Management, Ltd., with properties and installation methods that conform to ASTM F2207-02 [7]. As shown in Fig. 1, the CIPL consists of a seamless woven polyester hose with a thin interior polyurethane layer. The polyester hose is saturated with a two-part polyurethane that bonds the hose to the inside surface of the pipe. The installation of the CIPL is performed by the “inversion method”, in which the polyurethane-impregnated lining is inverted into an existing, previously cleaned pipe using either heated air or water to drive the inversion process and accelerate curing.

The woven polyester hose is composed of yarns that are orthogonal to each other and are oriented along its axial and hoop directions. Tension tests were performed by Stewart et al. [43] on 15-mm-wide and 200-mm-long samples in both axial and hoop directions following a modified ASTM D3039/D3039M-14 [8]. Test results are presented in Fig. 2 where force/width is plotted with respect to strain, in conformity with ASTM F2207-02 [7]. The data follow an approximately linear relationship until failure, with mean and standard deviation of strength, strain at failure, and secant stiffness of 170.6 ± 13.7 N/mm, 19.1 ± 1.5%, and 1000 ± 250 N/mm, respectively.

The linings were installed in DI pipe specimens with a nominal 150 mm diameter manufactured by the U.S. Pipe and Foundry Co. (US Pipe) and supplied by the Los Angeles Department of Water & Power (LADWP). The nominal 150-mm pipe outer diameter and wall thickness were 175 mm and 7.6 mm, respectively. All specimens had a 3.3-mm-thick interior cement mortar lining in conformance with AWWA C602-11 [6]. The modulus of elasticity, tensile strength and strain at rupture of the DI are 185 GPa, 417 MPa and 10.4%, respectively [53]. Fig. 3 shows a cross-section of a push-on bell-and-spigot joint. Bell-and-spigot joints are a cost-effective solution for water distribution networks, which allow for rapid construction. Because of the ease of the construction, it has been the most popular and frequently used type of joint

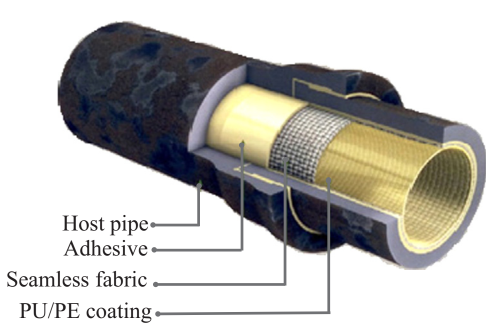

Fig. 1. Three-dimensional view of cured-in-place lining [40].

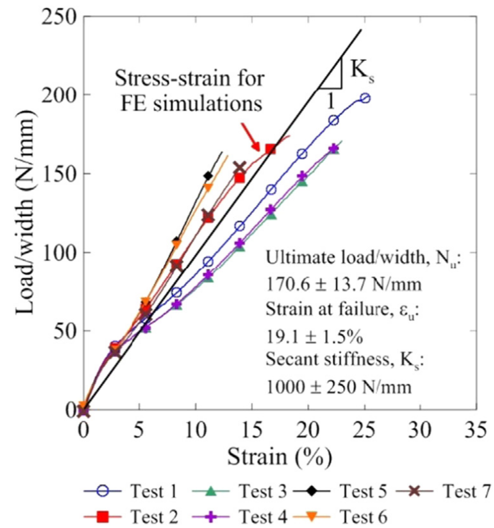

Fig. 2. Tensile test results for CIPL specimens oriented in the axial direction [43].

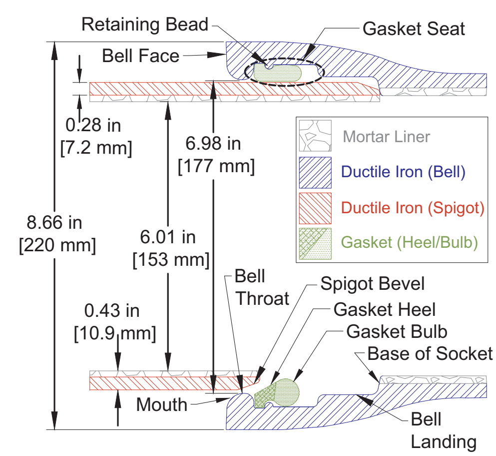

Fig. 3. Cross-section of a typical 150-mm push-on joint [53].

for ductile iron pipelines in areas that small ground deformation is expected. The joint is sealed with a greased rubber gasket. During field installation, the spigot is inserted into the bell until contact between the spigot and bottom of the bell, leaving typically a small circumferential gap, on the order of 3–6 mm. The force required to extract the fully inserted spigot from the bell varies from 0.67 to 0.89 kN [53]. Since the pullout capacity of DI joints is low with a full circumferential gap between the end of the spigot and back of the bell, they were used as proxies for CI pipelines with leaking joints or circumferential cracks, commonly encountered flaws. CI pipelines account for 38% of the US water distributions pipelines and are in operation for more 50 years, thereby constituting significant portion of the US aging infrastructure [21].

3. Permanent ground deformations effects

Permanent ground deformation (PGD) can arise from surface faulting, landslides, and liquefaction-induced lateral spreading and subsidence [32]. There are many ways in which seismic PGD affects underground pipelines, such as the oblique slip affecting pipelines crossing a fault plane in Fig. 4a. Strike slip may induce compression or tension, depending on the angle of intersection between the pipeline and fault. Fig. 4b shows a pipeline crossing a lateral spread or landslide perpendicular to the general direction of soil movement. In this orientation, the pipeline is subject mainly to bending strains and

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